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RF Filter Technology

Qorvo 2nd Special Edition

by David Schnaufer, Brian Robbins, Warren Strand, Gernot Fattinger, Robert Aigner, Fouad Boueri, Shawn Gibb, Igor Lalicevic, Mark Gallagher

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Introduction

The implementation of 5G and wireless applications is accelerating worldwide, along with the drive to deliver high data rates and high data capacity. This creates new challenges for wireless technology in many radio frequency (RF) device applications, because these trends increase the probability of interference. To mitigate that interference, RF filter technology is a must.

Bulk acoustic wave (BAW) and surface acoustic wave (SAW) technologies are evolving to address these challenges. These filter technologies are advancing toward handling higher frequencies, smaller device sizes, and increased interference.

This book provides a solid basic tutorial to RF filter technologies like BAW and SAW. It looks at these technologies and what's driving filter technology implementations, helping you understand the benefits that make it so necessary. It also surveys the current state of how system engineers are using filter technology, in both mature and cutting-edge applications. After reading this book, you'll understand how RF filter technology is revolutionizing the electronics engineering industry — and how it will continue to do so going forward.

Foolish Assumptions

It has been said that most assumptions have outlived their usefulness, but we assume a few things nonetheless! Mainly, we assume that you're a stakeholder in the technology or semiconductor industry with more than a passing interest in a technology like SAW and BAW. Perhaps you're an engineer, a design architect, a technician, a technical leader, a salesperson, a technology student, or an investor. We also assume that you have some knowledge of semiconductor technologies. As such, this book is written primarily for somewhat technical readers like you.

If any of these assumptions describes you, then this book is for you! If none of these assumptions describes you, keep reading anyway. It's a great book, and when you finish reading it, you'll know enough about RF filter technology to be dangerous!

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Icons Used in This Book

Throughout this book, we occasionally use icons to call attention to important information. You won't see the typical cute grinning faces or other flashing emoticons, but you'll definitely want to stop and pay attention! Here's what you can expect.

REMEMBER

Discover key definitions and essential takeaways.

WARNING

Watch out for these pitfalls, downsides, and drawbacks.

TECHNICAL STUFF

Explore highly technical aspects that may appeal to your inner geek.

Beyond the Book

Although this book is full of good information, we could only cover so much in 48 pages! So, if you find yourself wanting more after reading this book, just go to `www.qorvo.com/products/filters-duplexers`, where you can get to more information about Qorvo's RF filter technology and products.

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IN THIS CHAPTER

- Getting to know RF filters
- Comparing SAW and BAW filters
- Identifying the temperature coefficient of a filter and Q factor
- Learning how the filter coupling coefficient affects performance
- Understanding filter packaging

Chapter 1
Exploring RF Filter Technology

The rapid growth in mobile wireless data in the last decade has created an ever-increasing demand for new spectrum bands and new technologies to accommodate the thirst for wireless capacity. This demand is not only driving wireless technology advancements, but also increasing the need for more enhanced radio frequency (RF) filter technology to help reduce system interference, increase RF range and receiver capabilities, and improve coexistence.

In this chapter, you find out how RF filters work and the technology variations used in today's applications. This chapter kicks things off by presenting some basic facts about filters and the benefits they provide.

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Uncovering the Basics of RF Filters

New to RF filter technology? Start here, with these important filter terms and concepts that will help you throughout this book.

- **Attenuation:** An amplitude loss, usually measured in decibels (dB), incurred by a signal after passing through an RF filter. When referenced outside of the filter's passband, it is also referred to as *rejection.*
- **Cutoff:** The point at which a filter's response has fallen by 3 dB.
- **Insertion loss:** A loss of signal power in the targeted passband of the filter.
- **Isolation:** Separation of one signal from another to prevent unintentional interaction between them. For example, you might separate transmit and receive signals to prevent their interaction.
- **Passband:** The region through which a signal passes relatively unattenuated.
- **Q factor:** Short for *quality factor,* the ratio of stored versus lost energy per oscillation cycle. It's used to measure the selectivity of a resonant circuit.
- **Ripple:** The variation of insertion loss in the passband.
- **Selectivity:** A measurement of a filter's capability to pass or reject specific frequencies relative to its center frequency. Selectivity is usually stated as the loss through a filter that occurs at some specified difference from the center frequency of the filter.
- **Stopband:** The band where the filter has reached its required out-of-band rejection, defined as a required number of decibels.

Figure 1-1 illustrates a typical RF filter response using the terms as outlined earlier.

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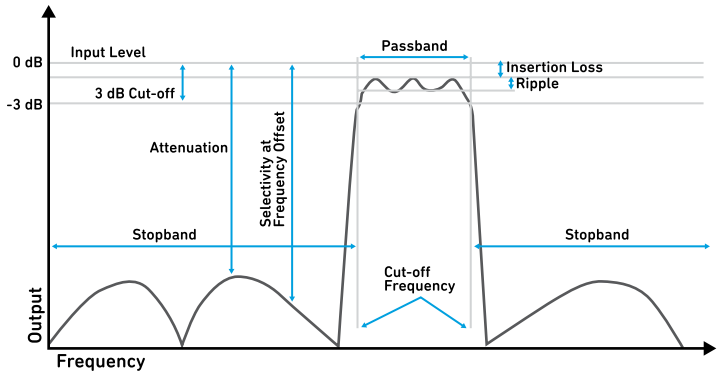

FIGURE 1-1: A typical RF filter response.

REMEMBER

A filter removes unwanted frequency components from a signal while preserving the desired frequency bandwidth. Four basic types of filters accept or reject signals in different ways, as shown in Figure 1-2:

- **Low-pass filter:** Allows all frequencies below a certain frequency to pass while rejecting all others (opposite of high pass)
- **High-pass filter:** Allows all frequencies above a certain frequency to pass while rejecting all others (opposite of low pass)
- **Band-pass filter:** Allows all frequencies between two frequencies to pass while rejecting all others (opposite of band stop)
- **Band-reject filter (also known as band-stop or notch):** Rejects all frequencies between two frequencies while passing all others (opposite of band pass)

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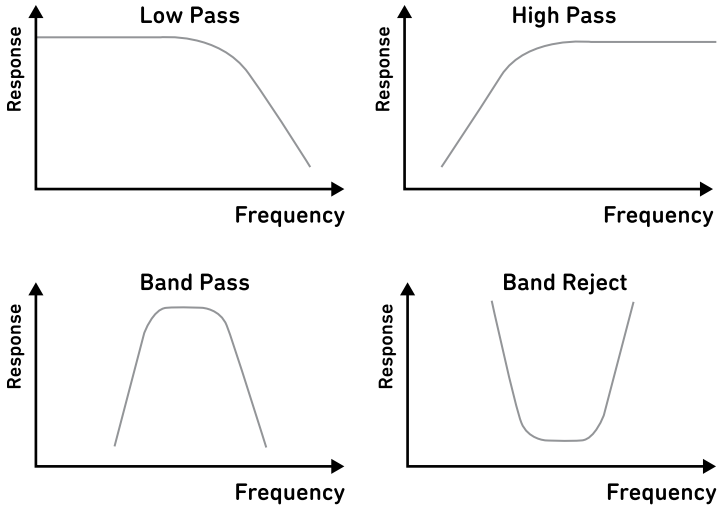

FIGURE 1-2: A basic RF filter and response.

Comparing Filter Technologies

Depending on application, a filter's construction will vary. The most common differentiators in RF filter technology are size, cost, and performance. The filter's construction plays a big role in these differentiators. Here are some examples of RF filter constructions:

- **Acoustic filter:** A filter capable of meeting both low and high frequencies up to 9 gigahertz (GHz), and in some special cases up to 12 GHz. These are small in size and offer the best combination of performance and cost for complex filter requirements. Acoustic filters are the most common filter construction for commercial RF microwave applications such as cellular, Wi-Fi, and Global Positioning System (GPS).
- **Cavity filter:** A filter used only in infrastructure applications. They can achieve good performance at reasonable cost but are larger than acoustic filters.
- **Discrete inductor-capacitor (LC) filter:** A low-cost structure of modest performance and size. The LC elements are sometimes implemented as printed structures on substrates called an integrated passive device (IPD). LC filters can also be implemented with discrete service mount device (SMD) components.

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- **Monoblock ceramic filter:** A more expensive, higher-performance filter than multilayer ceramic. They're also physically larger and usually aren't suitable for mobile applications.
- **Multilayer ceramic filter:** A low- to medium-cost filter with performance similar to that of LC filters. Its footprint is generally reasonable, but its thickness is greater, limiting its use in some applications.

Filters can be designed to meet a variety of requirements. Although they use the same basic circuit configurations, circuit values differ when the circuit is designed to meet different criteria. In-band ripple, fastest transition to the ultimate roll-off, and highest out-of-band rejection are some of the criteria that result in different circuit values.

REMEMBER

Filters allow only particular frequencies or bands of frequencies to pass through and are an essential tool for RF design engineers.

Exploring Piezoelectric Acoustic Filters

The most preferred filter technology used in many of today's applications are piezoelectric. These RF filters are small, cost-effective solutions used in many commercial, military, and scientific applications.

TECHNICAL STUFF

The *piezoelectric effect* is a reversable phenomenon of physics. The crystal substance generates electricity when under mechanical stress, and the reverse is true as well. The crystal will stretch by a tiny amount when an electric field or voltage is applied. The piezoelectric materials convert applied mechanical stress into electrical energy and can also transform electrical energy into mechanical strain.

The two acoustic filters on the market are surface acoustic wave (SAW) and bulk acoustic wave (BAW).

As shown in Figure 1-3, SAW and BAW filters can be divided into two topologies: ladder and lattice. Ladder-type filters present a steep rejection near the passband, but poor out-of-band rejection. Lattice-type filters provide good out-of-band rejection with less steep rejection near the passband. A hybrid ladder-lattice configuration offers a compromise between rejection and passband steepness.

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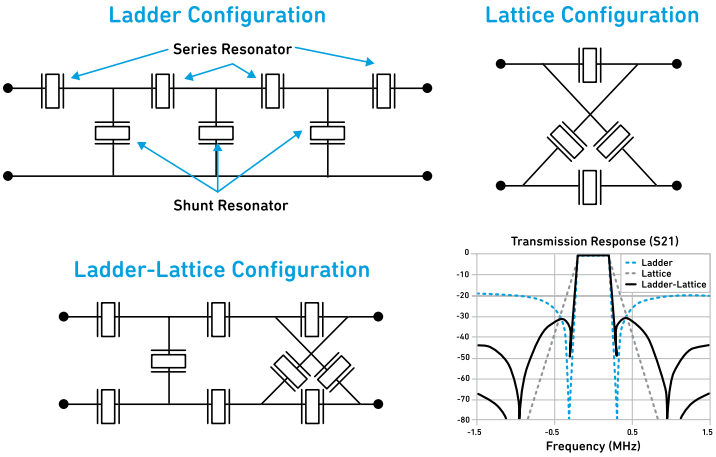

FIGURE 1-3: SAW and BAW configuration designs.

SAW filters

SAW filters are widely used and very mature. They laterally propagate high-frequency waves. As shown in Figure 1-4, an electrical input signal is converted to an acoustic wave by interleaved metal interdigital transducers (IDTs) created on a piezoelectric substrate like quartz, lithium tantalite ($LiTaO_3$), or lithium niobate ($LiNbO_3$). A SAW filter's low velocity enables it to fit many wavelengths across the IDTs in a very small device.

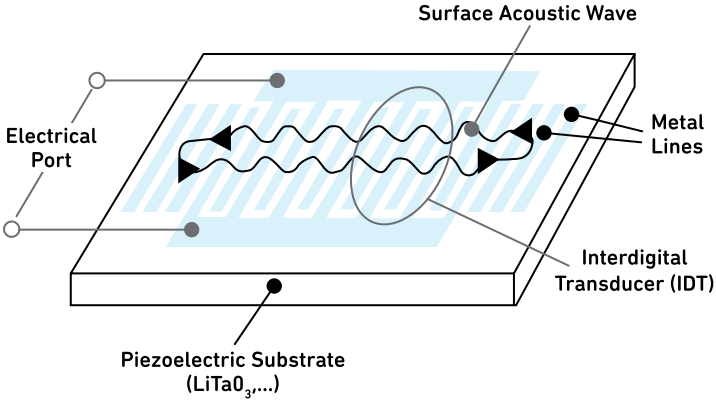

FIGURE 1-4: A basic SAW RF filter.

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A key advantage of SAW is its capability to optimally address standard filter applications from 600 to 1900 megahertz (MHz). It not only meets the low 5G bands at 600 MHz but also works well and is cost-effective in the low cellular bands of 1, 5, 8, 13, as well as the GPS bands.

To reach above 1900 MHz, layered SAW technologies — such as low-loss resonator technology (LRT), thin-film-SAW (TF-SAW), ultra-SAW, or incredibly high performance (IHP) SAW — are used. These technologies enable layered SAW to meet up to 2.7 gigahertz (GHz) for mid- to high-band applications. Above 2.7 GHz, SAW filter selectivity declines. However, where the SAW filter ends in performance, the BAW filter (covered later in this chapter) begins.

Temperature-compensated SAW

Among the many innovations in SAW technology is *temperature-compensated SAW* (TC-SAW). This type of SAW uses a thermo-compensated layer to avoid thermal drift, as shown in Figure 1-5. It performs at a higher level than standard SAW because of the greater temperature stability.

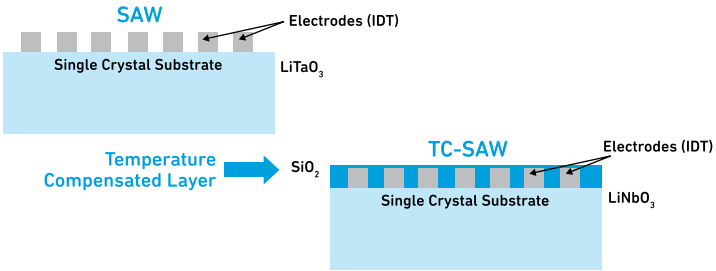

FIGURE 1-5: SAW versus TC-SAW.

TC-SAW devices on single crystal lithium niobate, along with burying the IDT electrodes in a layer of silicon dioxide (SiO_2), improves TCF and quality factor compared to traditional SAW-based filters and duplexers.

Implementing a temperature coefficient on SAW requires isolating the interdigital transducer (IDT) from any environmental temperature changes. To accomplish this, the SAW structure is covered with SiO_2 and sometimes an additional silicon nitride layer, as shown on the right side of Figure 1-5.

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TC-SAW improves filter characteristics to deal with the tight band allocations of LTE and 5G, as well as carrier aggregation (CA) for uplink and high-power user equipment (HPUE). Those improvements include lower insertion loss, steeper skirt characteristics, temperature stability, higher power durability, wider bandwidth frequency range, higher linearity, smaller size, and integration. To achieve these characteristics, a higher Q factor and a small temperature coefficient of frequency (TCF) are essential.

Layered SAW

In a traditional SAW substrate configuration, the acoustic wave propagating along the surface reaches up to a few wavelengths under the electrodes, and bulk wave radiation patterns appear deep into the substrate. This causes bulk acoustic wave leakage, reducing Q factor, TCF, and coupling.

One way to reduce this leakage is to create a new, multilayered structure or a variation of TC-SAW, such as layered SAW, as shown in Figure 1-6. Adding this additional layer of SiO_2 under the surface of the piezoelectric layer and functional layer provides an important benefit: A SAW propagating on the surface is guided in the piezoelectric layer and functional layer. As a result, the acoustic energy is confined in the vicinity of the surface, which improves the TCF and Q factor.

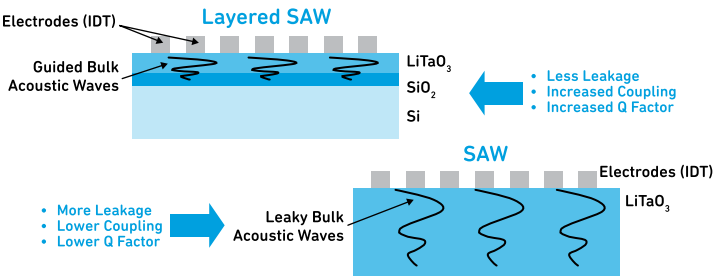

FIGURE 1-6: Layered-SAW versus SAW.

There are a few types of SAW filters on the market. They're known as SAW, TC-SAW, and layered SAW, which are also known as guided-SAW, LRT-SAW, TF-SAW, ultra-SAW, and IHP-SAW. They're all part of the family of SAW, using a layer

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like SiO_2 between the substrate and functional layer, as shown in Figure 1-6. Throughout this book, we refer to this type as *layered SAW.*

Layered SAW offers higher performance than the standard SAW filter. In some frequency bands, the layered SAW performance can even compete with BAW filters, discussed next.

REMEMBER

Layered SAW technology relies on piezoelectric material deposited on an insulator. In layered SAW, the thermal compensation mechanism comes directly from the substrate instead of being deposited on the surface over the electrodes.

Table 1-1 compares the different characteristics of acoustic-based SAW RF filter technologies.

TABLE 1-1 Qualitative Comparison of SAW Filter Technologies

Parameter	SAW	TC-SAW	Layered SAW
Structure	Single crystal piezo	Single crystal piezo	Single crystal piezo
Substrate material	Single crystal piezo	Single crystal piezo	Layered substrate
Performance	Good	Better	Best
Temperature coefficient	Good	Better	Best
Manufacturing cost	$	$$	$$$

BAW filters

The alternative to SAW is BAW. BAW filters address the frequencies between 1.4 and 9 GHz.

The main difference between BAW and SAW, besides the structure, is the piezoelectric material that the filters rely on. BAW filters use polycrystalline aluminum nitride, which provides higher coupling coefficient and higher wave velocity in the material.

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BAW filters can achieve very low loss because their acoustic energy density is very high, and the structures trap acoustic waves very well. Plus, their achievable Q factor is higher than other filter types of reasonable size employed at microwave frequencies. This results in superb rejection and insertion loss performance, even at the critical passband edges.

REMEMBER

The BAW filter offers lower insertion loss, which helps contribute to longer battery life in smartphone applications. BAW also excels in applications where the uplink and downlink separation is minimal and when attenuation is critical in tightly packed adjacent bands.

Unlike SAW filters, the acoustic wave in a BAW filter propagates vertically. As shown in Figure 1-7, the resonator uses a quartz crystal as the substrate. Metal paths on the top and bottom sides of the quartz excite the acoustic waves, which bounce from the top to the bottom surface to form a standing acoustic wave. The thickness of the slab and the mass of the electrodes determine the frequency at which resonance occurs. At the high frequencies in which BAW filters are effective, the piezo layer must be only micrometers thick, requiring the resonator structure to be made using thin-film deposition and micro-machining on a carrier substrate.

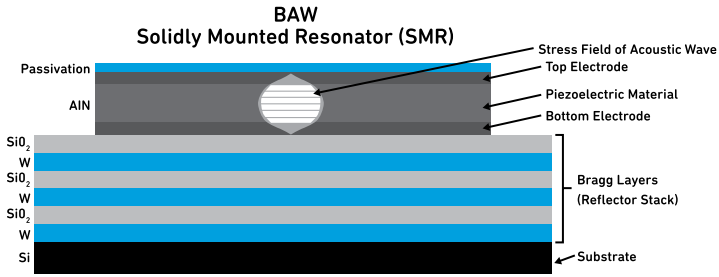

FIGURE 1-7: A basic BAW RF filter.

To keep the waves from escaping into the substrate in this type of filter, an acoustic Bragg reflector is created by stacking thin layers of alternating stiffness and density. The result of this approach is called a *solidly mounted resonator* (SMR) BAW, as shown in Figure 1-7.

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TECHNICAL STUFF

A Bragg reflector is a structure formed from multiple layers of alternating materials with varying refractive index.

There are two major types of BAW filters on the market, as shown in Figure 1-8: a solidly mounted resonator (SMR) BAW and a poly film bulk acoustic resonator (FBAR).

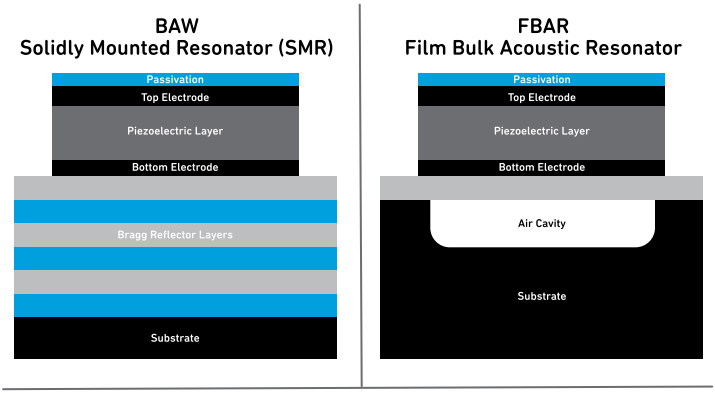

FIGURE 1-8: Cross-section comparing BAW filter technologies.

From a technology perspective, the big differentiators are substrate and air cavity between the substrate and bottom electrode. In Table 1-2, you see that stacked-layer BAW has the best temperature compensation.

TABLE 1-2 Qualitative Comparison of BAW and FBAR Filter Technologies

Parameter	BAW	FBAR
Piezo lattice structure	Polycrystal piezo	Polycrystal piezo
Resonator piezo material	Aluminum nitride (AlN) or scandium aluminum nitride (ScAlN)	AlN or ScAlN
Substrate material	Silicon	Silicon
Temperature coefficient	Best	Good
Acoustic reflector	Stacked layer	Air cavity
Manufacturing cost	$	$

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Some companies use their own brand names for FBAR or BAW technology, but they all fall under one of the two categories (BAW or FBAR). For example, XBAW is just another FBAR, while ultra-BAW is another BAW.

XBAR is a shear-wave BAW technology that is laterally field coupled. However, this technology is still in development and is not available in product.

Discovering the Temperature Coefficient of Filters

It seems each year brings new spectrum allocations in cellular, Wi-Fi, automotive, and so on. These additions of spectrum are good news, because they drive incremental improvements in wireless devices. But this additional spectrum sometimes comes at a price in areas where bands overlap each other. There is also an increase in system heat due to the additional RF pathways.

To ensure these signal paths are properly isolated from each other, RF filters with a low temperature coefficient are used. But not just any filter will do in many of these applications where spectrum is closely aligned to each other. As shown in Figure 1-9, cellular and Wi-Fi bands are sometimes close to each other — separated by only a few megahertz. RF filter technology like BAW is used to ensure coexistence between these bands.

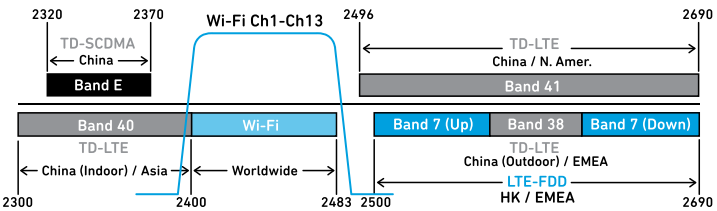

FIGURE 1-9: Examples of closely aligned Wi-Fi and cellular spectrum.

In both SAW and BAW technologies, a best-in-class temperature coefficient is vital. It can mean the difference between RF interference and good signal quality in an application. In BAW and SAW technologies, the filter response moves depending on temperature, as shown in Figure 1-10.

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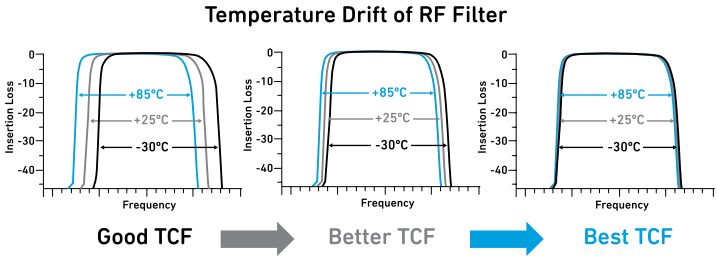

Technology	SAW	FBAR	TC-SAW	BAW	Layered-SAW
Temperature Coefficient Frequency (TCF)	≈ - 40 ppm/°C	≈ - 20 ppm/°C	≈ - 20 to near zero ppm/°C	≈ - 17 ppm/°C	≈ 0 ppm/°C

FIGURE 1-10: Temperature drift of piezoelectric filters.

As application temperature changes the filter response, the filter bandwidth drifts right when cold and left when hot. A filter's temperature drift is determined by the parts per million per degrees Celsius (ppm/°C) characteristic of the process and the temperature excursion the filter experiences in the application, as shown in Figure 1-10.

The frequency and environmental conditions of an application are usually fixed, so the only way to minimize the temperature drifting of the filter is via process technology. Using a temperature compensation (TC) filter process technology can affect the overall response of the filter. As you can see in Figure 1-10, the TC-SAW, layered SAW, and BAW technology processes greatly reduce temperature drift of the individual filters. These BAW, layered SAW, and TC-SAW process technologies offer lower insertion losses, create steeper filter skirts, and provide better temperature responses — which all equate to better out-of-band attenuation during temperature shifts. They also improve receiver sensitivity, isolation, and rejection.

REMEMBER

BAW filters are inherently less sensitive to temperature change than SAW filters. Temperature compensation (TC-SAW and TC-BAW) reduces temperature sensitivity even further.

In BAW, certain design techniques can be used to create a TC-BAW-type outcome, but generally BAW is effective when it comes to good temperature coefficient values. However, because of the structure makeup, there are differences between the three types of BAW when addressing the temperature coefficient.

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Figure 1-11 illustrates that the air cavity will likely affect the path of heat dissipation, thereby affecting the filter's temperature coefficient. The advantages of BAW over FBAR are more pronounced at the higher frequencies used in 5G and Wi-Fi. Power handling in filters becomes more challenging at the higher frequencies due to the smaller resonator size. However, with BAW, the reflector layers also become thinner, which further improves heat extraction.

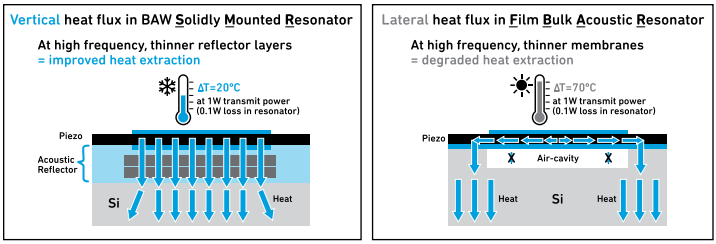

FIGURE 1-11: BAW versus FBAR filter power and heat handling.

In contrast, with FBAR, the membrane above the air cavity becomes thinner, reducing its capability to move heat away from the resonator. As a result, with insertion loss as a constant between BAW and FBAR, the temperature rises 20°C per watt of transmit power, compared to 70°C rise per watt with FBAR. Less temperature variation means better performance, which enables BAW filters to meet system requirements for insertion loss and out-of-band attenuation under high-power and high temperature conditions. Moreover, BAW filters have a low insertion loss due to their high Q factor and high coupling, which help reduce dissipated power and associated thermal issues.

Temperature challenges are also becoming constrained by today's high frequencies and smaller size applications. Moreover, the higher the frequency of a design, the greater the challenge of meeting parameter requirements. One of those key parameters is insertion loss. Line lengths, matching components, filter components, and connecting trace lines have an added effect on insertion loss. This is especially true in frequencies above 3 GHz. To optimize a system's link budget, low insertion loss filters are required.

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Evaluating the Q Factor

REMEMBER

Multiple factors determine a filter's insertion loss. Among these are the filter bandwidth relative to center frequency, the order of the filter, and the Q factor of the resonators that make up the component. The *Q factor* is a measure of the selectivity of a resonant circuit.

As shown in Figure 1-12, Resonator loss and coupling are the keys to low insertion loss and high selectivity. Resonators with similar coupling and impedance can be compared in performance by their Q factors.

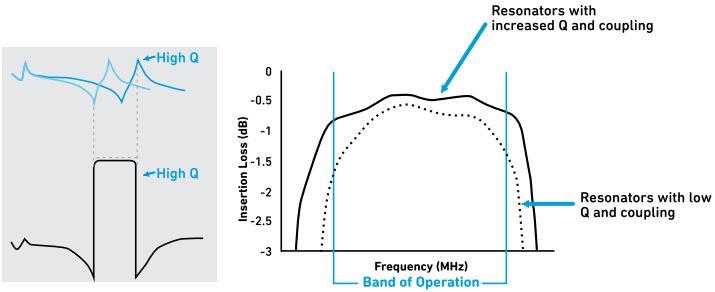

FIGURE 1-12: Q factor, bandwidth, and attenuation characteristics of an RF filter.

Exploring the Filter Coupling Coefficient

In filter technology, the two performance parameters that drive application performance are the filter coupling coefficient and the Q factor.

The RF filter resonator coupling coefficient plays a key role in determining the bandwidth of an acoustically coupled filter. Increasing the coupling effectiveness for a BAW filter resonator in an SMR or FBAR configuration can offer low insertion loss and high performance in a small package size.

Effective coupling coefficient (K^2_{eff}) is a measurement of the relative spacing between the resonance frequency (fs) and anti-resonance frequency (fp). Its value depends upon a multitude of factors, including the electrode and the piezoelectric characteristics.

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The electromechanical coupling coefficient is the measure of the efficiency of the piezoelectric device in converting electrical energy to mechanical energy and vice versa. The mutual energy, or energy capable of conversion, is the elastic energy and dielectric energy. To maximize the filter resonator's coupling coefficient, it's crucial to provide the reflection of the acoustic energy as close to the resonator as possible.

In the BAW filter, the effective coupling coefficient of the resonators defines the obtainable flat passband width of the filter.

Understanding Filter Packaging

The surface area of the radio frequency front end (RFFE) is shrinking in many (if not all) applications. This change is driven mostly by device size reductions and the need to make room for more consumer features.

Most of what we see today are module and monolithic integration, or the combination of both, inside one package. Figure 1-13 illustrates a highly integrated module that includes power amplifiers, BAW filters, and antenna switches. This, in turn, is incorporated into a complex system in package (SiP). This is just one of the complex modules that would be housed inside one SiP in normal applications.

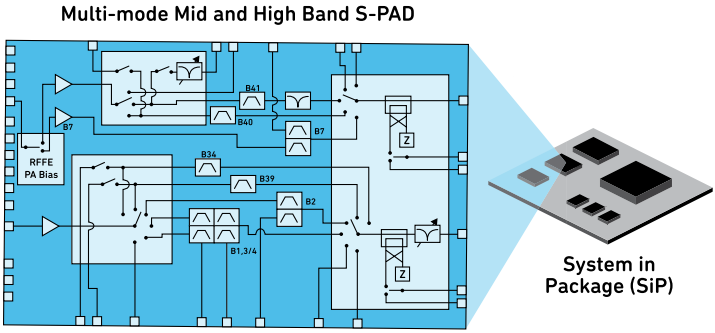

FIGURE 1-13: Complex RF module inside of SiP.

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IN THIS CHAPTER

- Understanding the crowded spectrum
- Identifying which filter works in what application
- Explaining multiplexers and antennaplexers

Chapter 2
Discovering the RF Front End and Filters

Filter technology is critical to mitigating crosstalk interference, maintaining peak signal performance, and optimizing system efficiency in gateways, cell phones, and other wireless devices. Without these filters, designers would struggle to meet many required system-level specifications that provide ubiquitous, always-on connectivity.

Filters make such a difference in today's end-product design because they help system engineers mitigate or entirely remove system-level challenges. Additionally, filters can reduce design time by creating viable go-to solutions for system designers.

In this chapter, you see how applications are driving a new era in radio frequency (RF) filter design in the RF front end (RFFE). You find out about families of filters and begin to explore duplexers, multiplexers, and antennaplexers, and see how they're used in today's applications.

Exploring the RFFE and RF Filter

The rapid growth of spectrum and the many frequency bands to accommodate the speeds and capacity requirements — along with the integration of new technologies like ultra-wideband (UWB)

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and cellular vehicle to everything (C-V2X) — are driving filter technology to help coexistence between many frequency bands. As a core component of the RFFE, RF filters are widely used in base stations, automotive, Wi-Fi, wireless communications, and more. In the following sections, we dig deeper into the technical aspects of filter technology and how it relates to the RFFE.

Understanding the role of duplexing

Duplexing enables two-way communications over a single communication channel. There are two basic modes of duplex operation:

- **Half-duplex:** The communicating parties take turns transmitting and receiving. While one party is transmitting, the other is receiving.
- **Full-duplex:** The communicating parties can transmit and receive simultaneously.

Full duplexing is achieved through frequency division duplexing (FDD), and half duplexing is achieved through time division duplexing (TDD), as shown in Figure 2-1.

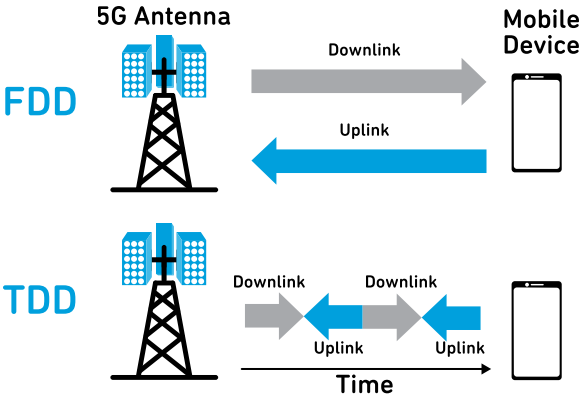

FIGURE 2-1: FDD versus TDD uplink and downlink.

FDD uses two separate frequency bands or channels to achieve full duplex communications. The two bands are physically separated in frequency (called a *duplex gap*) to prevent interference.

TDD emulates full-duplex communication over a half-duplex link, using a single frequency band for both transmitting and receiving.

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TDD assigns rapidly alternating time slots to transmit and receive operations of the communicating devices. Although TDD transmissions are concurrent rather than simultaneous, the intermittent nature of the communication is imperceptible to the communicating parties due to the high speeds at which TDD occurs.

Explaining isolation and cross-isolation

Duplexers are commonly used in FDD radio applications, where one filter is a transmit (Tx) filter and the other filter is a receive (Rx) filter. Duplexers are designed so that the passbands of each filter will not load the other.

Isolation is a measure of the amount of power that leaks from one RF port path to another. The greater the isolation between these RF pathways, the lower the leakage. If the isolation is low, then signals can bleed into one another causing interference, or desense (short for *desensitization*) in the case of the receiver.

The transmit signal appearing at the output of the receive filter must be significantly attenuated. This high level of isolation is required so that the signal doesn't overdrive the receiver's front end. This is often referred to as *transmit-receive isolation,* and values of 55 decibels (dB) or higher are common.

There must also be high Tx-to-Rx isolation at the receive frequency. This is to prevent noise at wide offsets from the transmit signal (that is, at the receive frequency) from appearing at the receiver input and degrading sensitivity. These two isolation requirements form the *in-band isolation.*

Isolation between RF pathways gets more challenging with each wireless device generation. For example, some smartphone models are now foldable, as shown in Figure 2-2. Not only are the phones incorporating numerous antennas to provide services in cellular, Wi-Fi, Global Positioning System (GPS)/Global Navigation Satellite System (GNSS), UWB, millimeter wave (mmWave), and Bluetooth ranges, but they're also challenged because now these pathways are folding over each other, making the possibility of interference more likely. This makes isolation between these RF pathways, standards, and closely aligned antennas even more important. RF filter designers must work even more diligently to meet more stringent isolation, passband, and attenuation parameters to ensure these foldable phones work without interference.

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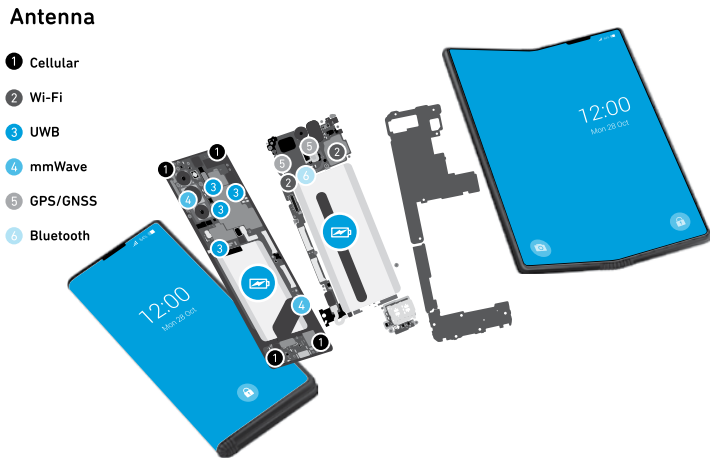

FIGURE 2-2: Foldable phones with multiple antennas.

Looking into RF receiver desense and sensitivity

Receiver sensitivity is the minimum detectable receiving signal power of a digital radio receiver. If a wireless receiver is desensitized, it means the noise floor is increased due to electromagnetic interference. This interference reduces the received signal-to-noise ratio, degrading the receiver performance throughput versus range.

Maintaining receiver performance amid RF interference and high receiving signal power is a major requirement for radio receivers.

Desense is the degradation in receiver sensitivity due to noise sources, which are typically generated by the same device radio it's in. Desense is caused by electromagnetic interference, which can come from an internal source or a strong self-generated interference within the system itself. Most often, the interference is self-generated.

Understanding RF front-end selectivity/coexistence

The ideal filter would have 0 dB insertion loss in its passband and negative-infinity dB in its stop band. Between the passband and stop band would be a transition from 0 dB to negative infinity.

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It would pass the required frequencies without adding or subtracting anything from the RF signal. However, a perfect filter like this can't be attained. Real-world filters have insertion loss, passband ripple, and nonzero gain in the stop band (refer to 1-1 in Chapter 1).

The transition band can be a defining characteristic in a filter's usefulness in a given application. The *transition band* is the steepness of the roll-off between the passband and the stop band.

The selectivity of a receiver is also very important. With the many RF signals being transmitted, the radio receiver must be able to receive only the required signal frequency and reject the unwanted signals. The receiver selectivity performance determines the level of interference the receiver will experience. Therefore, it's very important that the receiver rejects unwanted frequencies to enable interference-free performance.

TECHNICAL STUFF

Selectivity refers to the capability to filter out signals. In an RFFE receiver, selectivity is the capability to reject adjacent unwanted signals. Having superior insertion loss and out-of-band attenuation improves the isolation between signals on the receiver. High isolation between signal paths is also critical in limiting intermodulation products and meeting out-of-band emission specifications. Receiver filter performance is key when defining the selectivity.

Selectivity of a filter is also closely related to the quality factor (Q factor). Reducing the bandwidth of a filter increases its Q factor. The skirts become steeper, and the filter becomes more selective. Therefore, the band pass filter increases in selectivity as the Q factor increases. In general, designing a filter with superior selectivity is a trade-off between steep skirts, insertion loss, and Q factor.

The capability for a receiver to discriminate between signals is imperative. Receiver selectivity is usually discussed in terms of adjacent channel rejection (ACR), adjacent channel selectivity (ACS), in-band blocking, and out-of-band blocking.

Navigating a crowded spectrum

As we continue to jam more bands into the already crowded RF space, the space continues to get squeezed. In some cases, the transition between the passband and stop band is as small

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as 2 megahertz (MHz). This makes it challenging to meet system-level requirements. Any variation in filter response, which is dominated by temperature drift, can exceed the width of the transition band itself. This can result in interference, low signal quality, or both. This is where filters attribute the most. Figure 2-3 shows an example of how RF filters help separate Wi-Fi and the vehicle to everything (V2X) bands. Using filters with steep out-of-band transitions are a must in these types of situations.

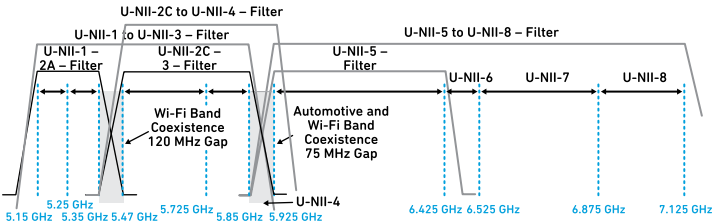

FIGURE 2-3: Spectrum of Wi-Fi and V2X bands.

REMEMBER

Because spectrum is a scarce resource, governments must ration it. This forces RF system designers to bear the brunt of the challenge in their designs, such as mitigating the evolving capabilities of several spectrum areas like Wi-Fi, automotive, Internet of Things (IoT), and cellular, all of which are converging upon each other as spectrum evolves. These technology bands require steep curve filters with little temperature drift and superior insertion loss to separate their signals or otherwise risk RF interference.

Learning how small device applications affect filter design

All wireless device solutions are shrinking in size. Today the Wi-Fi home and business architectures are called distributed Wi-Fi or Wi-Fi mesh. They're based on a "pod per room" architecture and are becoming more commonplace. These Wi-Fi pod access points or mesh network devices are becoming sleeker and smaller. In mobile smartphones, RF area is shrinking to accommodate larger batteries, more cameras, and more RF pathways. In wireless infrastructure towers, the RF portion is moving toward the top of the tower with the antenna, requiring the RFFE to be smaller and meet higher transmit and receive performance.

For example, the printed circuit board (PCB) in a smartphone is shrinking because of several factors. Phone manufacturers

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have increased battery size to support new features like additional cameras and antennas for UWB, mmWave, and diversity functions. To support the broad range of frequencies for Wi-Fi, low-band, mid-band, high-band, ultra-high-band, UWB, and mmWave, more antennas are required — up to six in many of today's smartphones (see Figure 2-4). This is forcing RFFE system designers to create smaller front-end components, including filters, in addition to integrating these filters inside small RFFE modules.

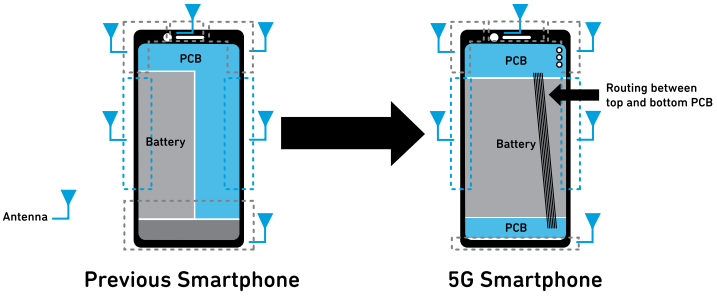

FIGURE 2-4: Larger batteries in 5G phones reduce the PC board space.

With the addition of all the new antennas to accommodate the many new and existing bands, high antenna performance is required. For high antenna performance, adequate antenna volume and spacing is required — and this is happening while space is becoming constrained.

Manufacturers face a tough architectural decision to meet this requirement previously solved using separate filters. They can try to add more antennas in an ever-shrinking area, with potential reduction in antenna and system-level performance. Or they can use a new development in design. This is where antennaplexers come into play — we delve more into that topic in Chapter 4.

Briefly speaking, *antennaplexers* combine multiple RF filters to allow several different radios — like cellular Wi-Fi, GPS, and UWB — to share a single antenna. They enable mobile devices to use the existing antenna area more efficiently, adding support for new bands with no impact on existing form factors or features. Antennaplexers reduce the need to have separate antennas, while addressing coexistence filtering and insertion loss requirements, as shown in Figure 2-5.

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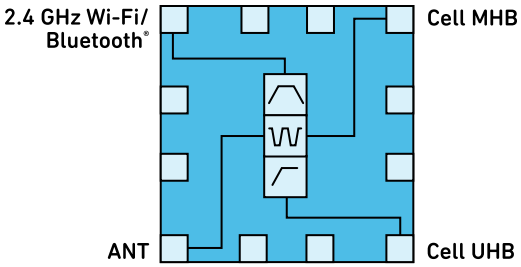

FIGURE 2-5: This antennaplexer enables a single antenna to be shared with Wi-Fi and cellular mid-bands and ultra-high bands.

Wi-Fi RFFE manufacturers are also taking advantage of front-end module technology to shrink the form factor, reduce the number of matching components, decrease the PC board space area, and create smaller, sleeker devices. By using front-end modules incorporating many RF pathways, as shown in Figure 2-6, system designers can save costs, cut design times, and get products to market more quickly.

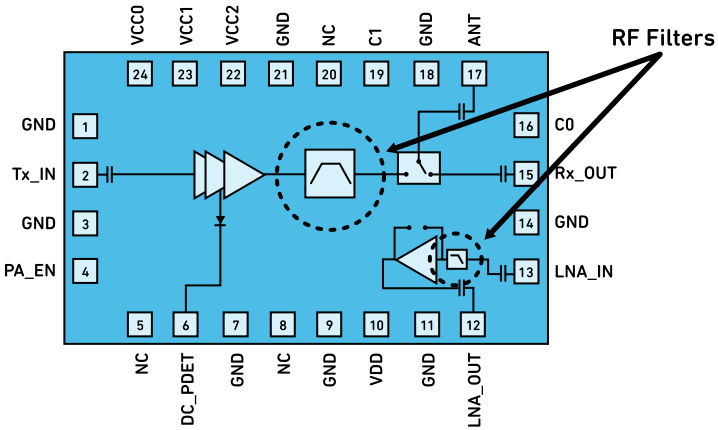

FIGURE 2-6: Wi-Fi RF front-end module with filters.

Adding multiple-input/multiple-output (MIMO) and higher frequencies in the 6 GHz realm has increased system temperature in Wi-Fi gateways. With more thermal and coexistence requirements, robust RFFE components that support high temperatures and multiple frequency ranges have become a must.

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To solve this challenge, more capable filter technology with temperature compensation has been developed. This, along with creating complete RFFE module solutions, has enabled system designers in the Wi-Fi gateway, automotive, and 5G spaces to meet their individual requirements.

Some filters used on the RF transmit side of the Wi-Fi RFFE can help increase signal performance. For example, when a Wi-Fi signal is close to the edge of the Wi-Fi channel band, such as channel 1, and the signal is transmitting at full power, some "bleed noise" outside the band can occur. This is commonly resolved by reducing the output power in these channels, but that reduces the output power signal output and range. RF filtering eliminates the need to reduce the output power in these situations, reducing the radio signal bleed outside the band. This enables the radio to transmit in these edge channels at maximum power range.

Introducing Multiplexers and Antennaplexers

REMEMBER

A bandpass filter and duplexer are no longer enough to ensure coexistence in today's complex RF devices. We need a more complex filter technology to support today's connective devices and their features such as mobile phones and gateways. These complex systems are where multiplexers and antennaplexers are useful.

What's the difference between these more complex types of filter technologies? Figure 2-7 shows the difference in a simple way. The antennaplexer operates near the antenna to help efficiently and effectively steer the proper signal deeper into the device. Antennaplexers reduce the need for more discrete components, as well as lowering the number of antennas used in the system. For example, an antennaplexer might combine GPS, Wi-Fi, and cellular bands, enabling one antenna to support all three RF pathways.

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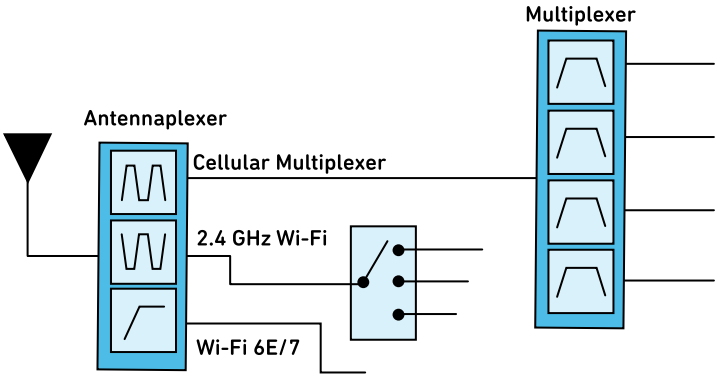

FIGURE 2-7: An antennaplexer and multiplexer in a block diagram.

Multiplexers operate further down the RF front-end chain, near the transceiver. Multiplexers separate the RF pathways, reducing system complexity and the need for many individual discrete RF filters. They also provide carrier aggregation (CA) support, enabling large capacity data throughput.

The next two chapters dig further into each of these filters to better understand their benefits and how they're used in RF systems.

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IN THIS CHAPTER

- Identifying the differences between duplexers, bandpass filters, and multiplexers
- Investigating filter isolation and cross isolation
- Comparing multiplexers and carrier aggregation

Chapter 3
Understanding Multiplexer Filters

This chapter goes into more depth about multiplexer filters and how they're used in various applications. You discover how multiplexers help designers create more complex wireless products.

Exploring Multiplexers

A multiplexer is a group of radio frequency (RF) filters that are combined in a way that they don't load each other and achieve high levels of isolation between their outputs (refer to Figure 2-7 in Chapter 2). Multiplexers are used within the RF front end close to the power amplifier (PA) and play an important role in carrier aggregation (CA), while antennaplexers are used after the radio frequency front end to simplify routing to the antenna. Multiplexer filters can include several types of filters all within one package. Figure 3-1 provides a high-level pictorial of several types of filters embedded inside one complex module design. These pictured individual duplexers, bandpass filters, and notch filters can also be part of a group of multiplexers called *quadplexers*, *pentaplexers*, and *hexaplexers.*, as shown in Figure 3-2.

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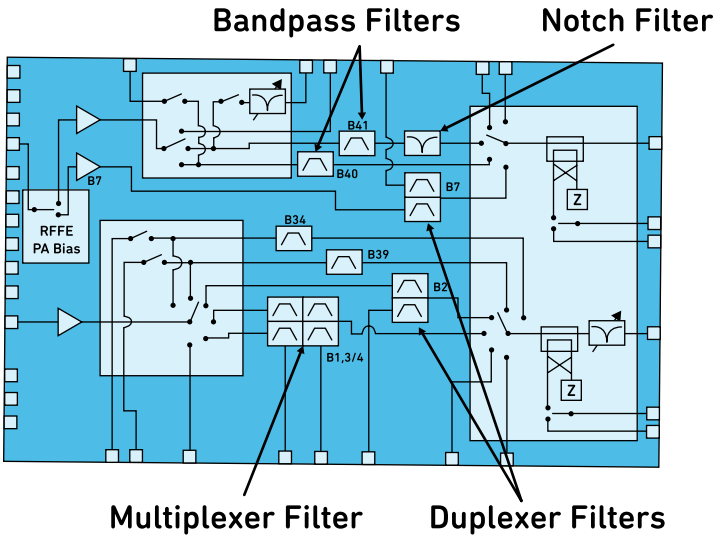

FIGURE 3-1: Bandpass filters, duplexers, notch, and multiplexer in functional block diagram.

A simple duplexer can be combined with other duplexers and filters to create more complex multiplexer designs. Like in the frequency division duplexing (FDD) bands are 1 and 3, and the time division duplexing (TDD) filter is band 41.

Today's wireless systems and devices must support more functionality, so they need ever smaller components. Integrating multiple non-overlapping filter bands into a multiplexer helps reduce component count and the size of the radio frequency front end (RFFE). Figure 3-2 shows some of the types of multiplexer designs to help reduce overall RFFE component count to meet new device size reductions. Multiplexers enable system designers to optimize, miniaturize, and simplify the overall design to meet system requirements.

Multiplexers provide an elegant solution, and in many cases the only practical solution, for carrier aggregation CA combinations that use closely aligned bands. Multiplexers integrate into a single component all the Tx and Rx filtering for aggregated component carriers (CCs), providing the required isolation while enabling multiple CCs to connect to the antenna at the same time.

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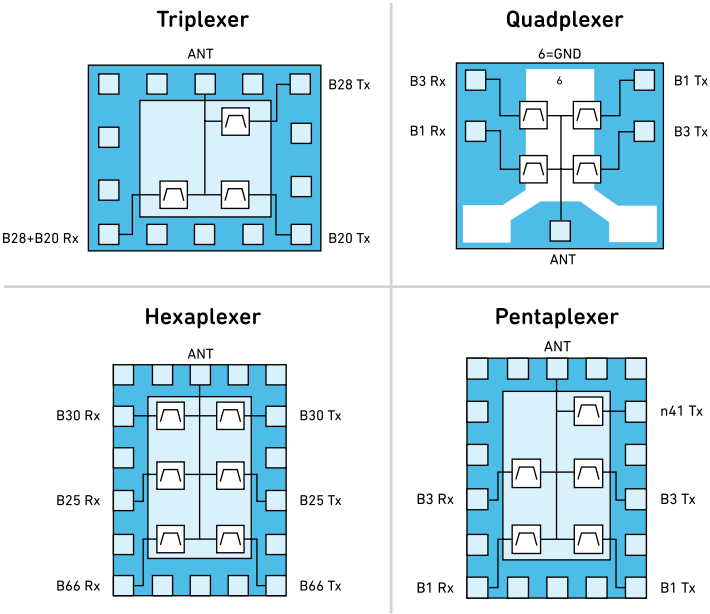

FIGURE 3-2: Types of multiplexer filters.

The multiplexer filters must be carefully co-designed and matched to achieve the required performance. Figure 3-3 shows a hexaplexer RF insertion loss for each of the filters. As you can see, each of the duplexers within this one multiplexer (hexaplexer) are matched for optimal insertion loss and passband. Additionally, the individual filters are designed to make certain they don't load each other.

REMEMBER

A well-designed multiplexer provides additional benefits to mobile device engineers because of the high level of integration they provide. Combining multiple filters into a single component will save on critical PC board space as opposed to using discrete filters.

WARNING

There are some discussions on using tunable filtering in these complex systems. However, using tunable filters may not improve system functionality because all of today's systems require the use of several RF paths simultaneously. A tunable filter may complicate accommodating this multipath functionality, so manufacturers have been pushing for higher-level multiplexer designs into more complex designs like an octaplexer, with eight functional RF pathways.

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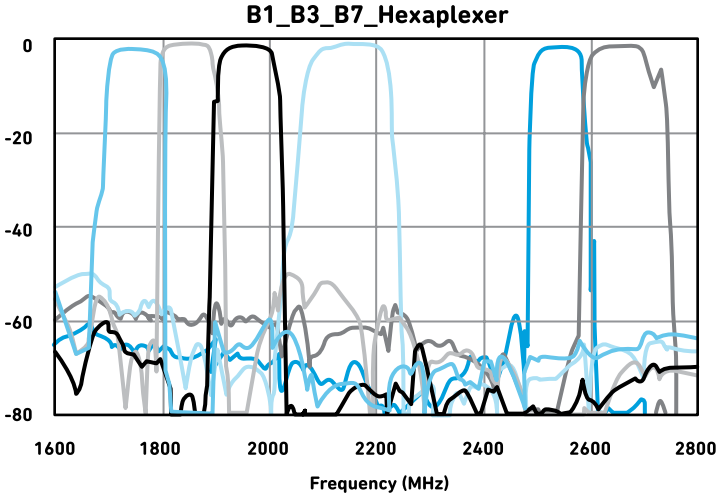

FIGURE 3-3: B1 + B3 + B7 hexaplexer filter insertion loss measurement.

Understanding Multiplexer Isolation and Cross-Isolation

As mentioned in Chapter 2, isolation and cross-isolation are important parameters requiring significant attention. *Isolation* is the capability of the filter to prevent a signal from showing up at a node in the RF circuit or system. Isolations such as those from a transmit or receive path need to be high so there's no way for these individual signals to bleed into each other.

Cross-isolation refers to isolation across bands, as shown in Figure 3-4. A duplexer requires the Tx signal to be attenuated significantly at its corresponding Rx frequency output. For a multiplexer like a quadplexer, the Tx signal must be attenuated significantly at both Rx outputs. Similarly, isolation of the Tx signal at the Rx frequency to control noise in the Rx band now must also apply at both Rx outputs. When you consider all the cases, there are eight isolations in a quadplexer that are important versus two in a duplexer. In Figure 3-4, we show the isolation measurement between band 1 Tx and Rx (top image). For the same component, we show the cross-isolation measurement between band 3 Rx and band 7 Tx (bottom image). Cross-isolation is the measure between two different Tx-to-Rx bands within the same component, while isolation is the measurement between the Tx and Rx of the same band.

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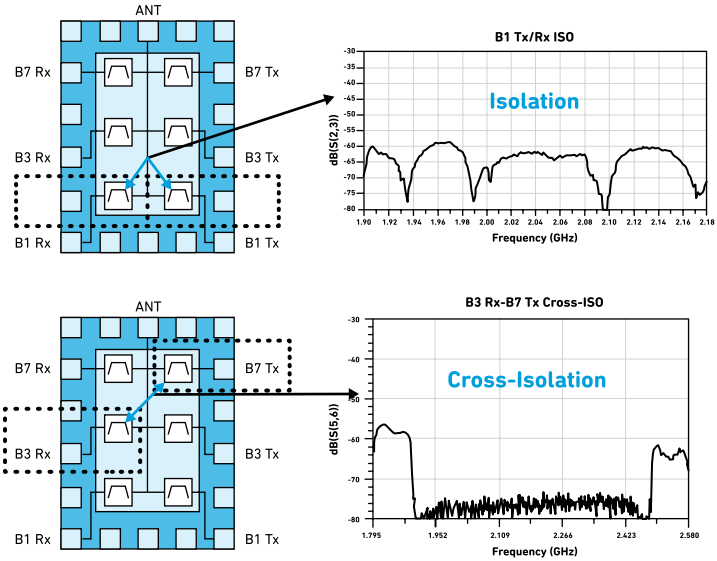

FIGURE 3-4: Band 1 RX isolation and band 1 and 7 TX cross-isolation measurement.

Multiplexers help achieve the required cross-isolation between the aggregated RF pathways, to enable simultaneous communication on all the aggregated carriers while attenuating the out-of-band (OOB) signals for each pathway.

Investigating Multiplexers and Carrier Aggregation

CA is another complex function of the RFFE. The advancements in filter technology have been critical to enabling the adoption of CA with Long-Term Evolution (LTE), 4G, and 5G. Filter material advancements in coupling, aluminum nitride enhancement, and material doping helped to achieve high OOB attenuation, low return loss, and the cross-isolation required for enabling multiplexer filter CA.

Multiplexers become increasingly important as the number of CA CCs increases. For example, aggregating three or more CCs significantly increases the probability of using close-together bands.

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These opportunities increase the probability of using a multiplexer like a quadplexer or hexaplexer.

CA enables microwave devices to create higher data rates by combining two or more carrier signals. CA is becoming very complex as more bands are being added to combination options. 5G defines hundreds of new combinations of up to 16 CCs, each with contiguous bandwidths up to 100 megahertz (MHz), for a total aggregated bandwidth up to 1 gigahertz (GHz).

CAs are divided into three types, as shown in Figure 3-5:

- **Intra-band contiguous aggregation:** Used if the spectrum blocks are adjacent within the same band.
- **Intra-band noncontiguous aggregation:** Used if the blocks are separated within the same band.
- **Inter-band aggregation:** The aggregation of spectrum in different bands. These bands may be widely separated or close together.

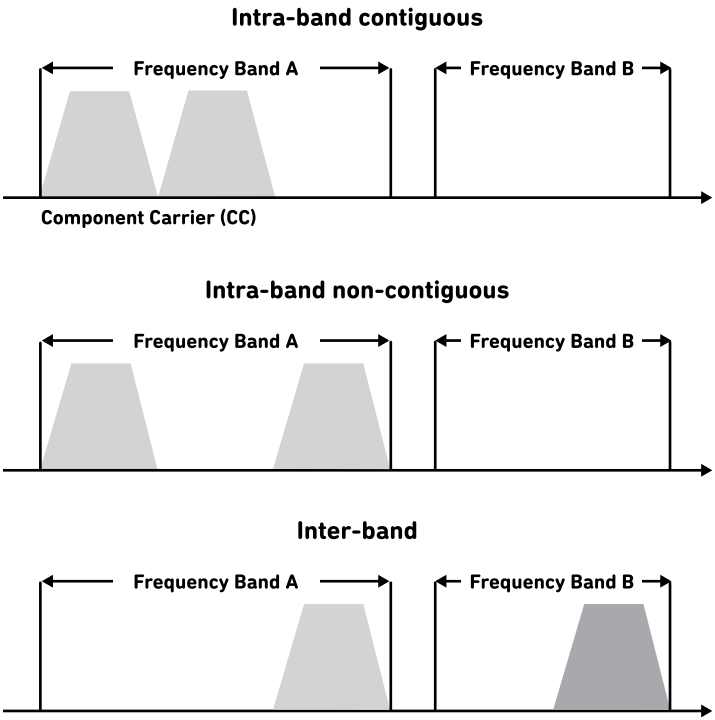

FIGURE 3-5: The three types of CA.

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Linear multiplexer filters with high OOB rejection allow for multiple CA combinations. Using the latest filter technologies like BAW, engineers have access to multiplexers featuring minimal insertion loss below or around 1 decibel (dB). This low insertion loss minimizes any negative effect on the power amplifier current drain and device battery life. An enhanced filter technology like BAW also provides best-in-class band isolation and cross-isolation for optimal system-level performance.

WARNING

It's important to note that CA creates a higher probability of interference. Multiband signals can interfere with each other due to insufficient filter attenuation. System desense (short for desensitization) can also occur when isolation or cross-isolation between the Tx and Rx paths is insufficient, creating a scenario where the sensitivity of the receiver is degraded.

A lower temperature compensated filter technology used in multiplexers is ideal to optimize isolation, attenuation, and OOB attenuation performance across bands to help designers mitigate these challenges.

Additionally, RFFE switches used with filters require ultra-high linearity and low insertion loss in a CA application. Because any increase in insertion loss may result in an increase in system noise, designers must figure in the receiver path. A poor insertion loss can also reduce overall PA efficiency, reducing battery life and device signal range.

Mobile devices feature high-speed up/down links to provide video and data. Receiver sensitivity can be affected by noise, which can affect signal reception. This noise can cause system desense.

REMEMBER

Desense is the degradation in receiver sensitivity due to noise sources, which are typically generated by the same device radio it's in.

EN-DC multiplexers and carrier aggregation

4G LTE-Advanced Pro supports up to five CCs. 5G New Radio (NR) CA supports up to 16 contiguous and noncontiguous CCs and can aggregate new 5G bands up to approximately 1 GHz of spectrum — as shown in Figure 3-6. Dual connectivity allows user equipment to simultaneously transmit and receive data. This along with CA increases data capacity of the network.

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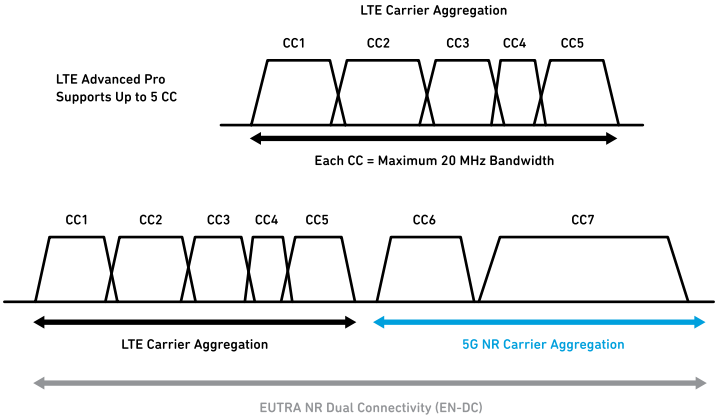

FIGURE 3-6: LTE and 5G NR CA.

Dual connectivity is also being used extensively in new 5G devices. Dual connectivity enables user equipment to simultaneously transmit and receive data on multiple CCs from two cell groups (a master evolved Node B [eNB] and secondary eNB). Using Evolved Universal Terrestrial Radio Access (EUTRA), which is a wireless air interface of the 3rd Generation Partnership Project (3GPP), plus 5G NR dual connectivity or E-UTRA NR Dual connectivity (EN-DC), networks can take advantage of 4G and 5G spectrum to increase user throughput, provide mobile signal robustness, and support load-balancing among eNBs.

Non-standalone and EN-DC

5G radio access network (RAN) is designed to work fully with the existing 4G LTE network. The 3GPP Release 15 standard allowed multiple NR deployment option such as non-standalone (NSA) and standalone (SA). For more information on NSA and SA, please read Qorvo's *5G RF For Dummies* book at `www.qorvo.com/design-hub/ebooks/5g-rf-for-dummies`. NSA utilizes a scheme very similar to CA. It combines an LTE anchor band for control and a 5G NR band to deliver faster data rates, as shown in Figure 3-7. NSA is a model of deployment where 5G services are provided without an end-to-end 5G network. This is where EUTRA plus NR dual connectivity is introduced. In EN-DC, both LTE and 5G NR carriers are used simultaneously. With EN-DC, two high-power RF signals are transmitted from one device. This

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configuration requires two complete uplink signal paths in the small device area of the smartphone. This presents major challenges to keep these two strong signals from interfering with each other. High isolation filtering is a must in these situations.

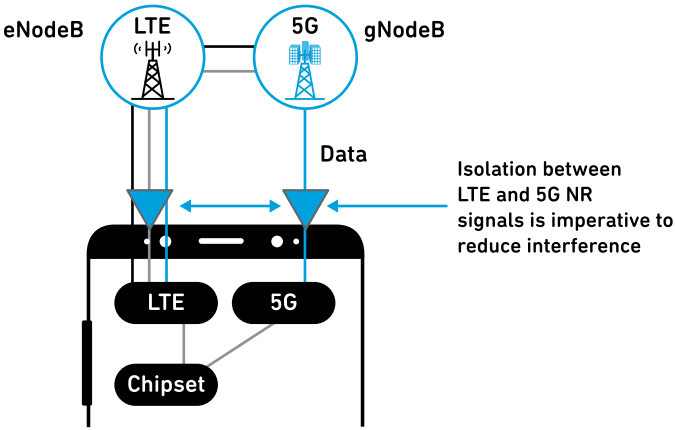

FIGURE 3-7: LTE and 5G NR CA.

High isolation between these two signal paths is critical in limiting intermodulation products and meeting OOB emissions specifications. Additionally, using high-isolation multiplexers between signal paths, the smartphone and mobile network operators can save battery life and energy because of the efficiency gained by providing coexistence between these two uplink signals.

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IN THIS CHAPTER

- Understanding how antennaplexers simplify and improve device designs
- Discovering how antennaplexers function within the RF front end

Chapter 4
Exploring Antennaplexers

Today's manufacturers face an important architectural decision. They can attempt to add more antennas in an ever-shrinking device area, with potential reduction in antenna performance and the resulting impact on overall performance. Or, they can use a new alternative, the *antennaplexer,* which reduces the need to add antennas and addresses coexisting filtering and insertion loss requirements.

In this chapter, you see how antennaplexers enable more features with fewer antennas and find out about the advantages of using them in many wireless applications.

Why Today's Devices Need Antennaplexers

Take a look back at Figure 2-7 in Chapter 2, which shows the differences between antennaplexer and a multiplexer. Notice that the antennaplexer is used near the antenna to reduce complexity, whereas the multiplexer is used closer to the radio frequency front end (RFFE), near the power amplifier (PA).

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Antennaplexers solve a key challenge facing wireless manufacturers of 5G systems: how to accommodate the dramatic increase in radio frequency (RF) complexity, while available antenna area continues to shrink due to evolving industrial design. Antennaplexers enable manufacturers to accommodate new 5G bands, 4x4 multiple-input/multiple-output (MIMO), diversity functionality, and other new requirements with fewer antennas and with no impact to existing form factors or features.

In mobile device Wi-Fi applications, antennaplexer filters play a key role in reducing design complexity and facilitating coexistence. They also help provide high isolation, which helps reduce that function on the antenna design and allows for less expensive antennas. As a result, the RFFE isolation parameter no longer needs to rest entirely on the antenna. This reduces antenna and shielding costs, providing up to 20 percent cost reduction.

The addition of new cellular and non-cellular bands has increased the total number of radio frequency (RF) paths in all wireless electronic devices — smartphones, automobiles, Wi-Fi gateways, and more. For example, a typical 5G smartphone that supports millimeter wave (mmWave) and ultra-wideband (UWB) bands has twice as many RF pathways as a legacy 4G phone. Many of today's handsets require six or more antennas for primary cellular and diverse receive functions (refer to Figure 2-4 in Chapter 2). Each RF path needs to connect to an antenna, but it's simply impossible to double the number of antennas due to the limited space available.

Moreover, increasing the number of antennas means they must be closer to each other, which reduces the isolation between them. This can cause coupling-related issues, increasing the potential for nonlinear elements in the radio frequency front end (RFFE), which causes desense (short for *desensitization*) on the receiver.

Figure 4-1 shows the many frequency bands; notice how closely aligned they are. For example, Wi-Fi 2.4 GHz and GPS L5 are located between low and mid–high cellular bands.

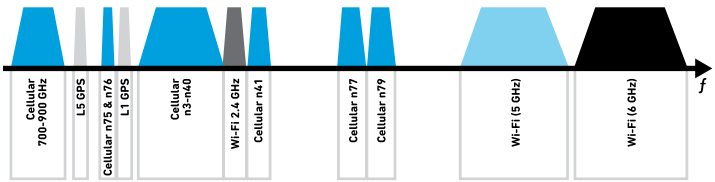

FIGURE 4-1: Multiple frequency bands used in smartphone devices.

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Antennaplexers help these individual bands coexist with each other. They reduce antenna complexity for engineers by allowing one antenna to transmit a large bandwidth. This large bandwidth is then split by the antennaplexer into multiple bands. Without antennaplexers, more antennas and switches would be required.

Antennaplexers play a key role in separating individual low, mid, and high cellular bands, Wi-Fi, and GPS (L5, L1) signals, while simultaneously providing interference mitigation and reducing system losses. In Figure 4-2, the top mobile smartphone image shows many individual filters on the antennas. Additionally, the upper-left image has three antennas. The bottom smartphone image shows how the introduction of antennaplexers in this design can reduce complexity, component count, and size. As shown in the bottom image on the left, using an antennaplexer, you can reduce the number of antennas from three to one, as well as taking the component count from four to one. Moreover, on the right side of the bottom image, adding an antennaplexer reduces the component count from four to two. This demonstrates how antennaplexers provide system engineers the ability to create designs easier by using antennaplexers.

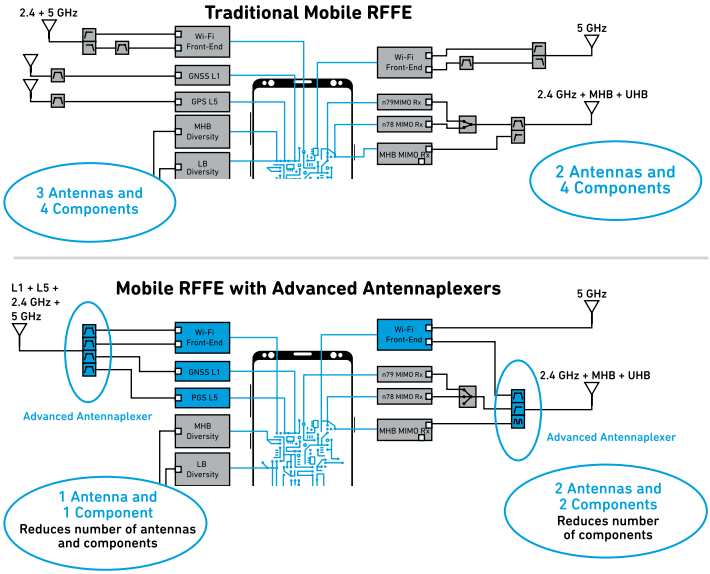

FIGURE 4-2: With and without antennaplexer solutions on a smartphone.

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REMEMBER

Antennaplexers provide many advantages to system and module designers. They not only reduce the number of antennas required, but also maximize performance while reducing system level desensitivity. They also enable greater design flexibility to support architectural and industrial design changes. Antennaplexers enable devices like smartphones to use the existing antenna area more efficiently, adding support for new bands with no impact on existing form factors or features.

Diving Deep into Antennaplexer Technology

Now that you understand *why* antennaplexers do their jobs, let's take a look at *how* they do it. In this section, you explore the types of antennaplexers and isolation.

Understanding the types of antennaplexers

Figure 4-3 shows several varieties of antennaplexers — all using a single shared antenna. For example, the triplexer shown in the upper-right side of the figure splits the Wi-Fi, mid-band, and ultra-high bands going to one antenna while providing the out-of-band (OOB) rejection needed for optimal coexistence. The remaining two antennaplexers shown in Figure 4-3 function similarly but do so by addressing cellular, Wi-Fi, and Global Navigation Satellite System (GNSS) in a system. However, multiple combinations of antennaplexer filters can be achieved.

Exploring antennaplexer isolation

As with the multiplexers, antennaplexers must also have high isolation between filters and bands, as shown in Figure 4-4. The figure shows the global positioning L5 and GNSS filters that were measured for isolation in this antennaplexer. The graph to the right is the measured level of signal isolation between these two filters within the one package design. Antennaplexers based on acoustic filters generally offer the best performance because they provide low insertion loss, address OOB rejection for multi-band coexistence, and provide high isolation between the RF frequencies sharing the antenna. At the same time, they support the ultra-high frequencies used for 5G, Wi-Fi, and UWB.

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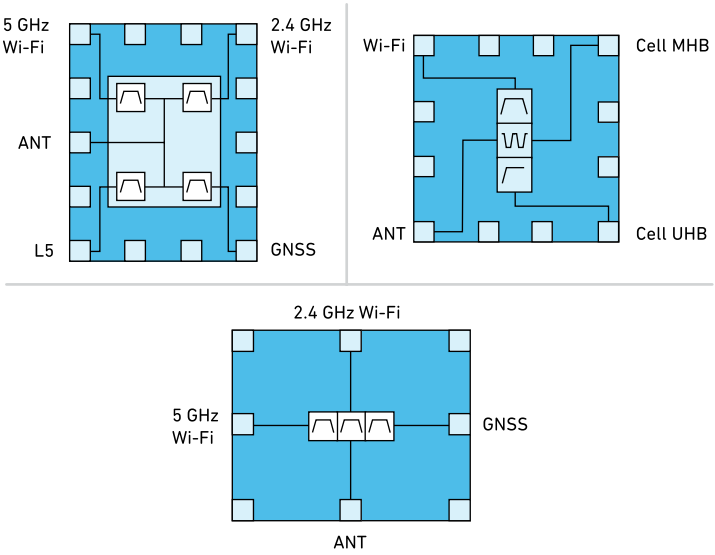

FIGURE 4-3: Example of some antennaplexers.

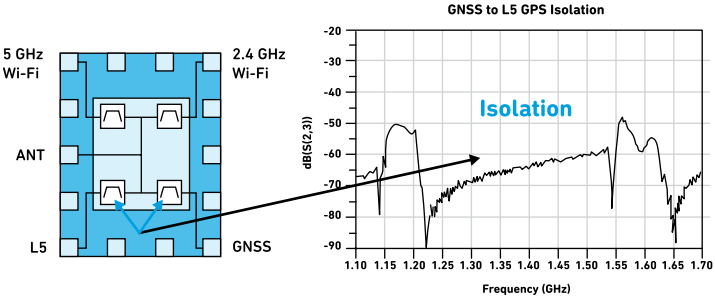

FIGURE 4-4: Antennaplexer isolation measurement.

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IN THIS CHAPTER

- Summarizing the benefits of RF filter technology
- Reviewing the basic technologies involved in RF filters
- Understanding the roles of multiplexers and antennaplexers

Chapter 5
Ten Key Takeaways

In a hurry? Start here! This quick list summarizes the key points from this book. Read these, and then if something catches your attention, check out the complete explanation in earlier chapters.

- **Spectrum is scarce, and radio frequency (RF) filters help sort out the many spectrum bands.** RF filter technology used in wireless gateways, smartphones, base stations, and many other devices mitigates crosstalk interference, maintains peak signal performance, and optimizes system efficiency.
- **The piezoelectric effect is a reversable phenomenon in physics.** The crystal substance generates electricity when under mechanical stress, and the reverse is true as well: The crystal will stretch by a tiny amount when an electric field or voltage is applied. The piezoelectric materials convert applied mechanical stress into electrical energy and can transform electrical energy into mechanical strain.
- **Bulk acoustic wave (BAW) technology provides the best heat extraction.** BAW has a stacked reflector without air gaps, making it much better than alternatives when trying to meet stringent device heat and performance requirements.

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- **Filter isolation is a measure of the amount of power that leaks from one RF port path to another.** The higher the isolation between RF signal paths, the lower the leakage. High isolation and cross-isolation in a filter mean the signal will be less likely to bleed into one another causing interference and desense (short for *desensitization*).
- **Desense is a degradation in receiver sensitivity.** Receiver desense can occur when there is a noise source that may likely be generated by a device in the radio itself. Properly isolating the individual signal paths using high-isolation RF filters can prevent a signal or noise from occurring on another pathway in the radio.
- **Cross-isolation is the isolation across bands.** A duplexer requires the transmit (Tx) signal to be attenuated significantly at its corresponding receive (Rx) frequency output. For a multiplexer like a quadplexer having two duplexers, the Tx signal needs to be attenuated significantly at both Rx outputs, not just its corresponding one. For example, a band 1 and 3 quadplexer will require the band 1 Tx to significantly be attenuated from both the Rx band 1 and band 3. The same goes for the band 3.
- **Multiplexers help system designers optimize, miniaturize, and simplify their designs.** For example, a smartphone will have many RF pathways. A multiplexer is used to consolidate several RF pathways using fewer devices to reduce system complexity, path-loss, and size.
- **Multiplexers are an important factor in carrier aggregation (CA).** The aggregation of three or more component carriers (CCs) significantly increases the probability of using close-together frequency bands. Multiplexers help achieve CA while mitigating signal interference.
- **Antennaplexers provide many advantages to system designers.** Implementing an antennaplexer on a design like a smartphone can reduce the number of antennas, maximize performance and system-level sensitivity, and allow for more design flexibility.
- **Antennaplexers combine multiple RF filters into one package.** Antennaplexers allow several different radios — like Wi-Fi, Global Positioning System (GPS), ultra-wideband (UWB), and cellular — to increase the number of bands capable of sharing a single radio antenna in a device.

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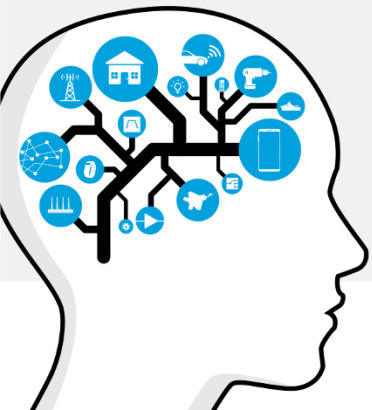

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Discover RF filter technology

RF SAW and BAW filter technologies are used in many mobile, Wi-Fi, automotive, GPS, and cellular infrastructure applications. These RF filter technologies allow the many bands within these wireless applications to function in harmonious coexistence. Although these filter technologies have been around for many decades, they have evolved to meet the many new challenges seen in today's complex communications systems. RF filters help provide many technology advancements in the microwave arena — like carrier aggregation, Wi-Fi coexistence in automotives, antenna signal path management, and RF signal range boosting in Wi-Fi gateways.

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Inside...

- Understand RF filters' unique material properties
- Learn how RF filters are used in many of today's wireless applications
- Discover how RF filter technology enables next-generation complex designs
- Find the best filter technologies for your application
- Learn the secret behind coexistence

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